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THREE DEGREE-OF-FREEDOM FORCE FEEDBACK CONTROL
FOR ROBOTIC MATING OF UMBILICAL LINES

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ABSTRACT

NASA is currently investigating the use of robotic manipulators for the mating and demating of umbilical fuel lines to the Space Shuttle Vehicle prior to launch. Force feedback control is necessary for this task in order to minimize the contact forces which will develop during mating. The objective of this project is to develop and demonstrate a working robotic force control system at Kennedy Space Center.

Initial experimental force control tests with an ASEA IRB-90 industrial robot using the system's Adaptive Control capabilities indicated that control stability would be a primary problem. An investigation of the ASEA system indicated a 0.280 second software delay between force input commands and the output of command voltages to the servo system. This computational delay was identified as the primary cause of the instability. Tests on a second path into the ASEA's control computer using the MicroVax II supervisory computer indicate that the time delay would be comparable, offering no stability improvement. All existing inputs to the ASEA control computer hardware were found to have too long of a delay for force control stability.

An alternative approach was developed where the digital control system of the robot was disconnected and an analog electronic force controller was used to control the robot's servo system directly. This method allowed the robot to use force feedback control while in rigid contact with moving three degree-of-freedom target. Tests on this approach indicated adequate force feedback control even under worst case conditions. A strategy to combine the analog force control system along with the existing digitally-controlled vision system was developed. This requires switching between the digital controller when using vision control and the analog controller when using force control, depending on whether or not the mating plates are in contact.

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The Robot Application and Development Laboratory (RADL) at Kennedy Space Center has been established to investigate robotic solutions to launch vehicle processing problems. The intent of the laboratory is to provide a testbed where robotic components can be used to develop workable engineering solutions for hazardous and repetitive shuttle and payload processing activities.

One such task is the mating and demating of umbilical fuel lines for the main tank of the Space Shuttle Vehicle (SSV). Presently, the umbilicals must remain attached to the SSV until slightly after launch, so that in case of a launch abort, the fuel can be rapidly removed to make the launch vehicle safe. Explosive bolts and a mechanical tear-off feature are used to disconnect the lines immediately after launch, offering the possibility of damage to the shuttle during launch. The present manual methods of reconnecting the fuel lines after a launch abort require over fifteen hours, and include numerous safety problems to both the technicians and astronauts. The ability to use a robot to disconnect the umbilicals prior to launch and then reconnect them rapidly in case of an abort would offer a major improvement in launch safety.

The umbilical mating problem places extensive demands on the sensory capabilities of the robotic system. First, the SSV is a dynamic structure, continually moving in a random fashion. Second, the mating problem requires high relative positioning accuracy between the umbilical connectors. Finally, the forces encountered during contact must remain low to avoid damaging either the umbilicals or the SSV.

Three distinct phases must occur for umbilical mating using a robot. The first phase involves the use of vision tracking to allow the robot to approach and track the umbilical target. The second phase requires an actual mating process to occur. This will require a combination of mechanical guidance, compliance, and active force feedback control and is the least understood task of the problem. The third phase happens after a solid mating has occurred. In this case, the random motions of the SSV must be duplicated by the robot using a force feedback approach to avoid large contact forces. Practically, the SSV must be able to lead the robot around such that the contact forces remain below a maximum tolerable value.

A major goal of the RADL is to provide a feasibility demonstration of this capability by using both force and vision information to dock and mate a simulated umbilical plate with a moving target. To do this, force feedback control will be required on the existing ASEA IRB-90 robot.

Previous work on force feedback with the ASEA robot indicates a very high tendency for instability under operating conditions required by the umbilical mating problem. The goal of this work is to identify the instability problem and develop a stable and effective force control system.

2.1 DAMPING CONTROL

The theoretical difficulties of arbitrarily controlling a combined vector of force and position have been dealt with by several authors, as summarized in reference [1]. However, the practical implementation of these approaches requires the implementation of extensive algorithms based on an accurate mathematical model of the robot.

One simple yet quite effective approach to force control is that of damping control, also known as trajectory perturbation and accommodation control. With this approach, the velocity of the robot is proportional to and in the direction opposite of the applied force, acting like a pure damping element. In effect, the robot moves so as to relieve the forces generated during contact. The proportional constant between velocity and force is defined by the force feedback gain K_f .

2.2 DESIGN REQUIREMENTS

Force control is required to both guide the umbilical lines in the chamfered socket during mating as well as allow the robot to track the dynamic motion of the SSV after mating. Contact forces under both conditions must not exceed the forces currently encountered during manual mating. For this study, this value is assumed to be 60 pounds. A worst case estimate of the dynamic motion of the SSV [2] is a sinusoidal motion with a maximum amplitude of 6 inches and a frequency of 0.2 Hz., leading to a maximum speed of 11 inches per second. Based on these requirements, the minimum value for the force feedback gain for tracking is 0.18 in./sec./lb.

An inherent condition for any control system is stability. An upper limit for the force feedback gain is selected to be one half of the gain for marginal stability, providing a gain margin of 2.0. The control design problem is thus reduced to selecting a gain greater than 0.18 and less than half the marginal stability gain.

2.3 STABILITY

It has long been known that communication and computational delays in control systems have an adverse effect on the system stability. This is especially true in the case of force feedback. For example, consider a pin

using force feedback control inside a 1 degree-of-freedom hole. Without a delay in the force feedback signal, contact with one side of the wall results in a command motion to move away from the wall, with the commanded speed going to zero when the pin is centered. This behavior is demonstrated in Figure 1a. With a significant delay, the velocity command always lags the force, resulting in cases where the commanded velocity is in a direction which increases the contact force, as shown in Figure 1b. This can result in instability.

A very simple model is used to predict marginal stability order-of-magnitude estimates for both force feedback gain and time delay. The model assumes ideal dynamics of the robot and no force interaction with the servo system. Using a time lag of 0.280 seconds as found in the ASEA controller, the maximum gain for stability is found as 0.015 in./sec./lb. This results in a maximum force feedback gain of .0075 with a gain margin of 2.0. This result is 24 times too low for proper force tracking. Requiring a value of 0.18 for the force feedback gain K_f results in a maximum time delay of 0.044 seconds for stability. Note that both estimates do not take into account the robot's dynamics, and are upper limits on practical values.

2.4 SINGLE AXIS VS. MULTIPLE AXIS CONTROL

The velocity response of the robot to an applied force should be directly opposite to the direction of the force. In general, this requires actively controlling all six axes. The ideal force-velocity relationship for damping control therefore requires coupled response between the motor axes and the applied force. This multiple-input multiple-output (MIMO) relationship between the force vector and the axis velocity command is described by the kinematics:

$$V = K^{-1} J(\theta) F$$

where:

- V is the desired velocity vector
- K is the damping control gain matrix
- J is the Jacobian matrix
- θ is the angular position of the links
- F is the measured force and torque vector

A simplifying approach is to control individual axes which are relatively coupled to the TCP axes of the force/torque sensor. This can be represented as:

$$V = K^{-1} K_1 F$$

where:

- V is the desired velocity vector

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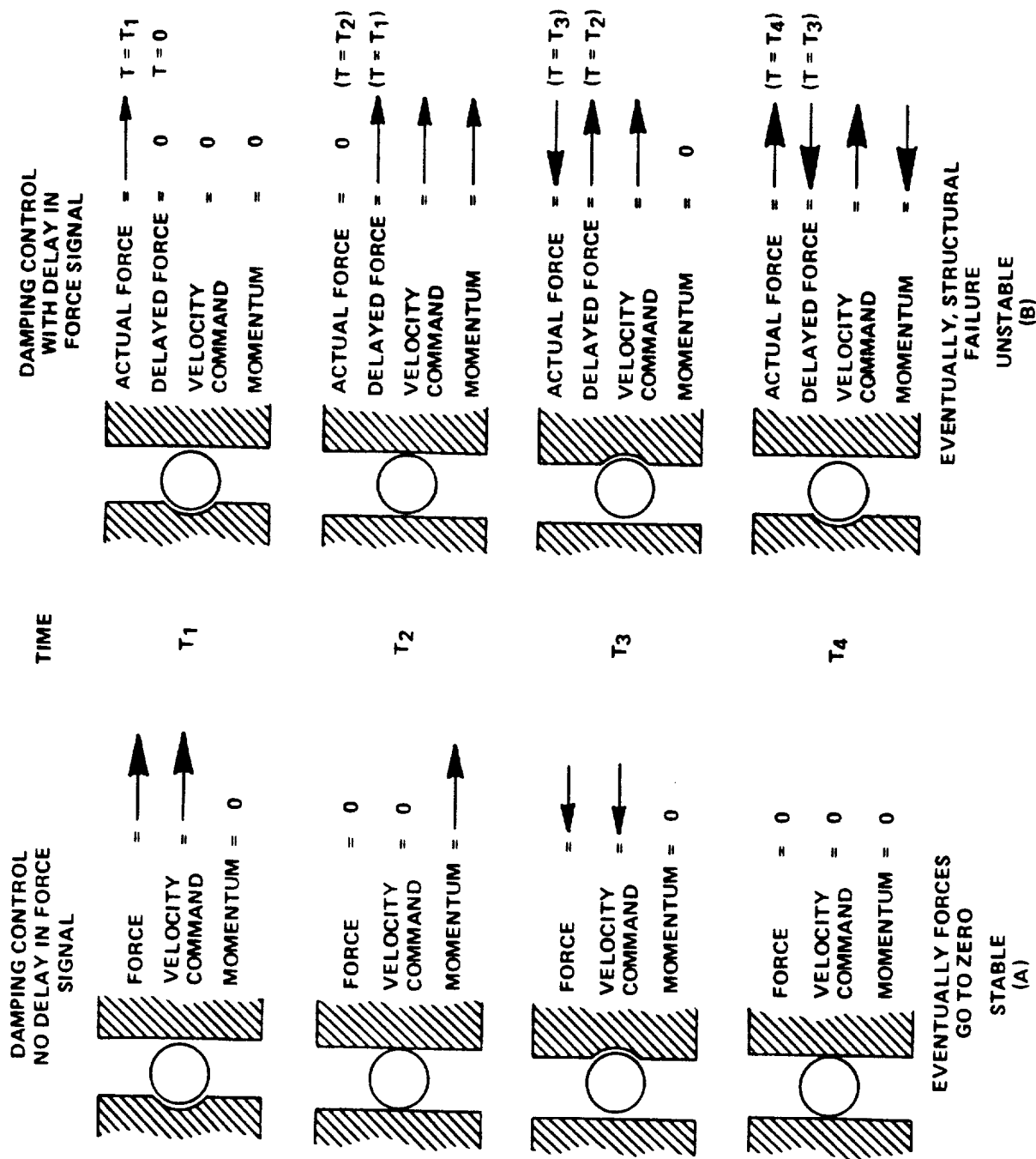


Figure 1. Damping Control Instability due to Control Time Delay

K is the damping control gain matrix
Kl is a fixed coordinate transform in the force/torque sensor
 $K * Kl$ is diagonal matrix
F is the measured force and torque vector

This approach allows each axis to be treated as an individual single-input single-output (SISO) systems over a small range.

This SISO approach will be used in this study due to simplicity. The requirements for implementation of the superior MIMO approach will be discussed in the summary.

2.5 COMPLIANCE

An inherent requirement for the damping control approach is a degree of compliance or elasticity either in the robot itself or through the addition of an external compliant element between the applied force and the robot. For a stiff robot in contact with a rigid objects, the amount of motion of the robot need only be a few thousandths of an inch to cause a wide change in the force level. The addition of passive compliance can greatly increase the positional change for the same force level. In effect, the passive compliance decreases the force sensitivity to positional changes. Therefore, the force control algorithm must be able to operate under a wide range of possible compliance values.

An experimental test was performed to determine the ASEA robots compliance. A lead screw was used to apply force the robot about the base rotation axis while under positional control of the robot's servo system. Force was measured using the JR3 six axis force/torque transducer while position was measured by a machinist's dial indicator. The elastic coefficient for the robot in this position was found to be 407 +/- 15 Lbs. with a 0.015 inch backlash. This value is position dependent, but it provides an approximate baseline value for typical values.

3.0 IMPLEMENTATION OF FORCE CONTROL

3.1 ASEA CONTROLLER OVERVIEW

The implementation of force feedback control depends completely on the capabilities built into the ASEA control computer. The controller is very well designed for industrial purposes, but can only use as designed by ASEA. Internal modifications in the controller software are impractical

due to ASEA's insistence on not releasing software documentation due to proprietary reasons.

The ASEA controller consists of two separate controllers, referred to as the control computer and the axis controller. The control computer determines trajectories, system status, and performs kinematic calculations. The axis control consists of a digital proportional position control loop surrounding an analog electronics velocity control loop for each link. The positional error determined by the digital controller of the ASEA is converted to a digital signal and used as a reference velocity command for that axis.

The controller allows only two paths for incorporating external sensory input, referred to as Adaptive Control and Supervisory Control. An overview of the possible methods for force control is shown in Figure 2.

The classical problem of gain versus stability is encountered. A sufficient gain for force tracking is too large for stability. The conclusion is that the time delays encountered using either the MicroVAX II or Adaptive Control inputs to the ASEA will not allow stable force control using values which would meet the force tracking capabilities of the robot.

3.2 ADAPTIVE CONTROL OPTION

The ASEA robot has an input option designed for contour tracing, which implements a simple damping-based force feedback control algorithm. This option, known as the Adaptive Control option, refers to adapting the robot's trajectory in real-time due to external sensory input, rather than the more traditional designation referring to parameter adaptive controller compensation systems. This input allows direct force feedback control from the force/torque sensor into analog communication port of the robot controller. This port was previously instrumented by the author [3] during the 1987 Summer Faculty program and is currently being used in a 3 D.O.F. lead-around demonstration.

While this port was originally designed by ASEA to implement force feedback control, it has several drawbacks. The adaptive control feature allows 3 D.O.F. of MIMO force control in a rectangular (RECT) coordinate system, keeping the orientation of the robot terminal device constant, as desired for umbilical mating. However, a controller error causes a robot error, halting motion of the robot. This is unacceptable in a contact situation.

Use of the MODRECT coordinate system uses a force controller which works without these problems, but only on a SISO basis. Again, this approach works well in lead-around demonstrations, but has been previously shown to be unstable at control gain values within those required by the design constraints.

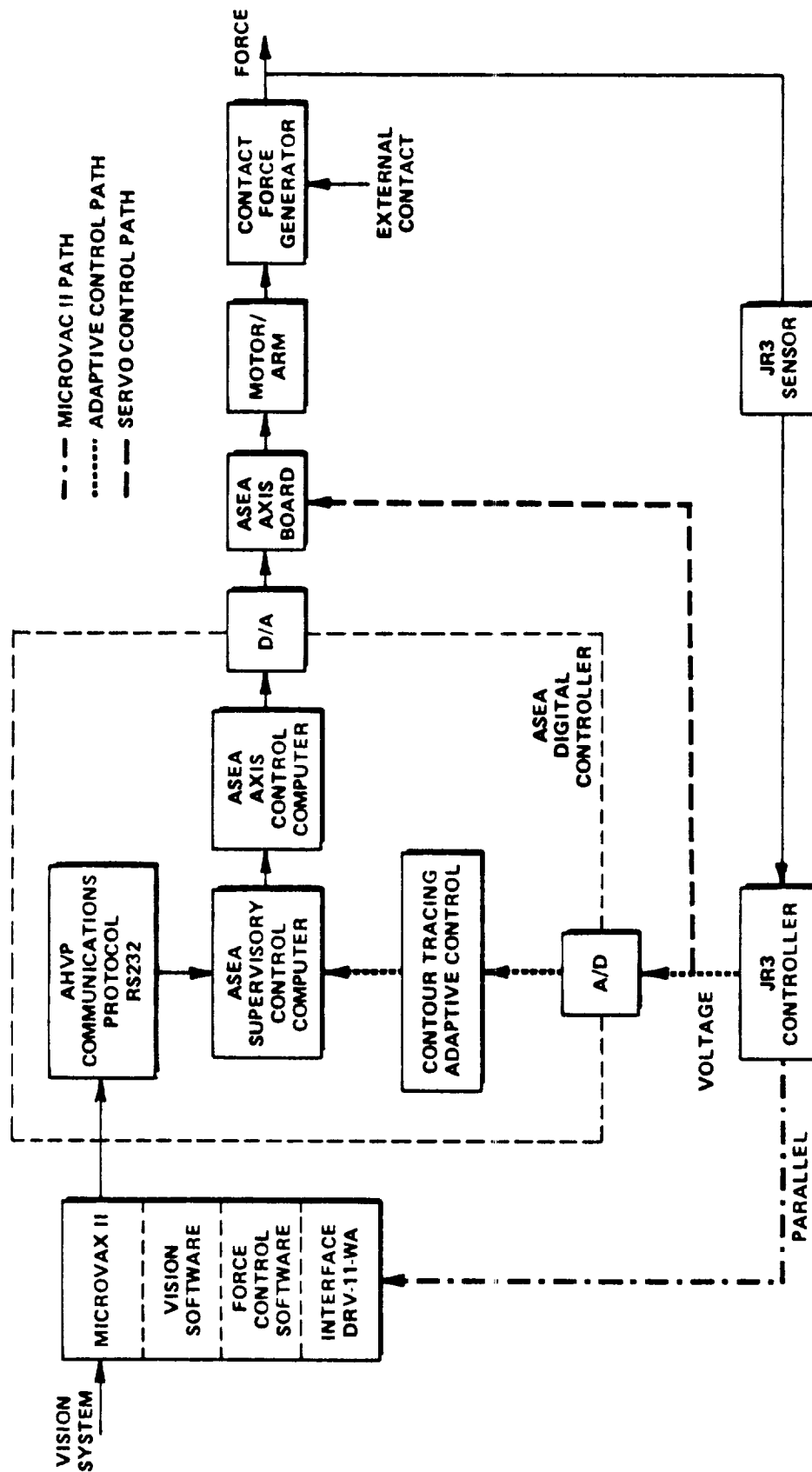


Figure 2. Possible Paths for RADL Force Feedback Control

Test data was taken with a digitizing oscilloscope to determine the direct delay between the adaptive control input port and the command output to the servo drive system indicated a delay averaging at 285 milliseconds.

A classic demonstration of the effect of this delay on stability is provided in Figures 3 and 4. In both cases, force feedback was implemented using the adaptive control (contour tracing) feature of the ASEA. Only a slight change in the feedback gain determines whether the system is stable or unstable. Note that the marginally stable gain value for K_f of .018 in./sec./lb. is 20 times (using an appropriate gain margin) below that required by the design specifications. Notice also the extensive delay time between the force measurement and the resulting servo command.

Contact with support engineers from ASEA indicate that they were unaware of the extent of this delay, and indicated that there is no immediate solution to this delay problem. Further, ASEA will not provide the means to modify to the controller software stored in EPROM or the software documentation.

3.3 SUPERVISORY CONTROL

The primary path into the ASEA controller is through the Supervisory Control method. This approach allows an external computer to determine the trajectory of the robot and pass the command positions directly to the ASEA controller in an open loop fashion. This approach is presently being used successfully with the 6 degree-of-freedom (D.O.F.) vision control system. In this instance, positional errors are determined by a complex vision system, which passes these errors on to a MicroVAX II computer. This computer in turn passes the desired absolute position of the robot to the ASEA controller through a communication protocol known as AHUP.

This approach has several advantages for force feedback control. First, all control calculations can occur in a single computer. Second, the force and vision control can be easily integrated. Finally, this approach allows for the implementation of a MIMO force feedback control algorithm in world coordinates for all six degrees of freedom, with the ASEA controller performing the necessary kinematic calculations.

The problem with this approach is the extensive communication protocol overhead of the AHUP communication package along with the computational speed of both the MicroVAX II and the ASEA control computer. The extensive delay of this approach creates extreme difficulties in stabilizing the robot.

A rough estimate of the expected delay using this approach can be determined by using data from a test of the vision system delay time. In this test, a vision target was given a step positional change which was recorded along with the command to the analog servo system. Results are shown in Figure 5. Notice that there appears to be approximately a 350 millisecond

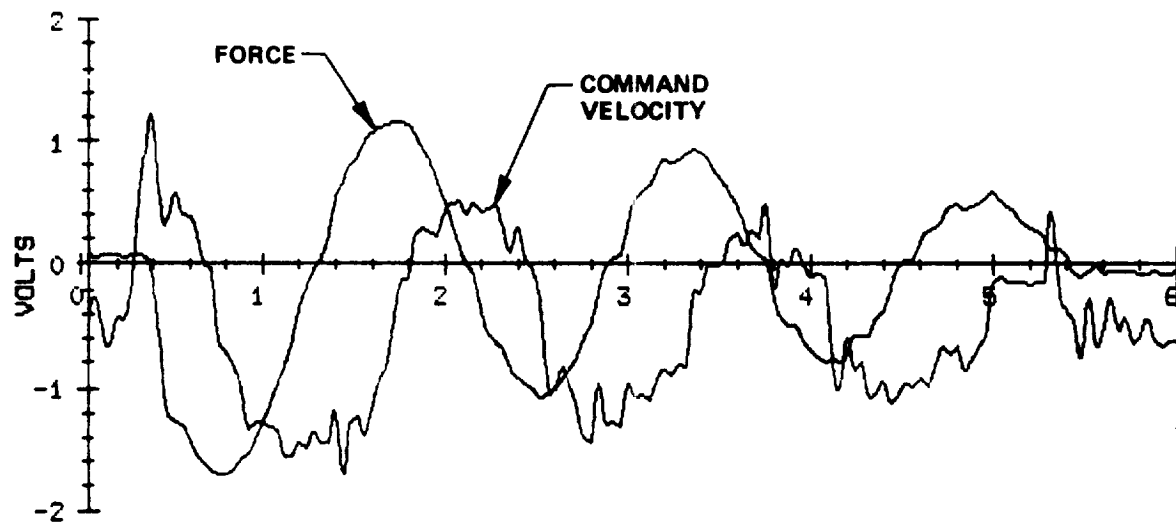


Figure 3. Force Feedback Control Stability Using ASEA Adaptive Control Force Feedback ($K_f = 0.018$ in/sec/lb)

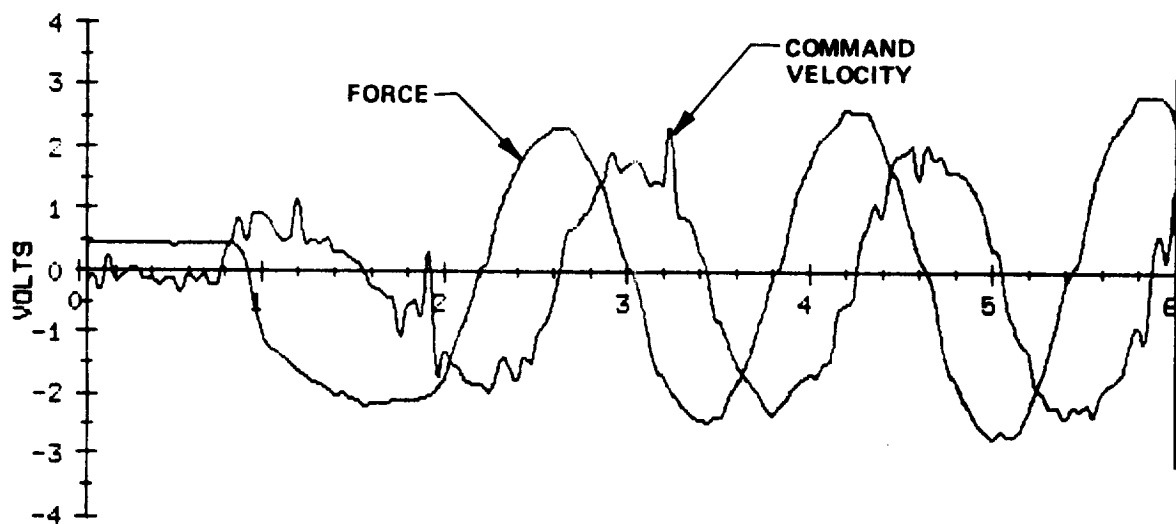


Figure 4. Force Feedback Control Stability Using ASEA Adaptive Control Force Feedback ($K_f = 0.020$ in/sec/lb)

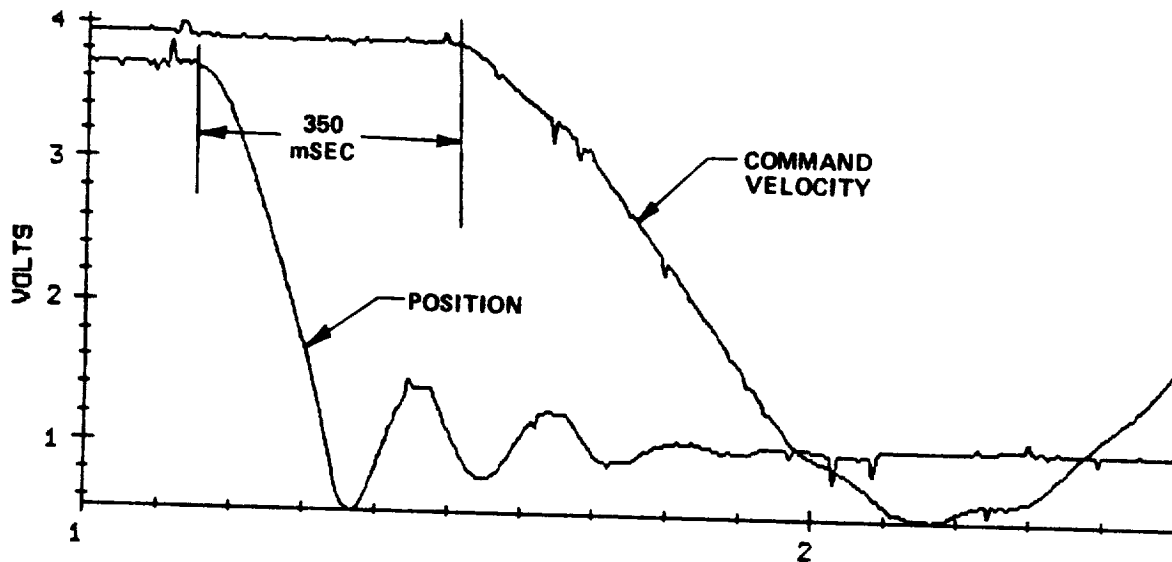


Figure 5. MicroVax - ASEA Controller Time Delay
Using Vision System

delay between initiation of the movement and the initiation of the servo control signal.

The following table lists estimates of the computation time for the vision control process, along with an extrapolation of the lag which would be encountered by using force feedback through the MicroVAX II.

ESTIMATED TIME DELAY COMPONENTS OF VISION SYSTEM

TIME (msec)	TASK
33	Camera refresh rate
33	System 1000 processing
10	System 1000 to MicroVAX II communication
?	MicroVAX II and ASEA control delay
350	Total Delay Time

Result: MicroVAX II and ASEA controller delay: 274 msec.

Notice that the computer time delay is comparable to that encountered using the Adaptive Control inputs. Since force control through the MicroVAX II

link can be no faster than the present vision control algorithm, the conclusion is that force control implementation using the MicroVAX II will not allow for stable force feedback control at gains which will allow adequate tracking.

3.4 ADVANCED ALGORITHM DEVELOPMENT

There has been considerable theoretical development in control theory, including methods to handle stability problems associated with time delays [4]. The most commonly used approach is that of the Smith predictor, where a detailed model of the robot's dynamics without delay is used to predict the dynamic response and cancel the delayed value. Notice that this approach takes delay only out of stability argument, not out of system, and requires an accurate mathematical model of the dynamic behavior of the robot. Attempts were made to develop such a model. However, the signal-to-noise ratio of the measured variables was too low for simple non-stochastic modeling. There were also modeling problems associated with the nonlinearities of the system, including positional controller gain, backlash behavior during contact as well as position-dependent elasticity variations.

Under such conditions, the identification required for an accurate model of the robot under contact conditions would require a considerable amount of engineering effort. With a simple model, the question of the algorithms robustness to modeling inaccuracies is in question. Esoteric approaches such as a parameter-adaptive Smith predictive control algorithms make for interesting research, but would prove very difficult to implement.

4.0 ANALOG CONTROLLER APPROACH

4.1 ALTERNATIVE APPROACH: AN ANALOG FORCE CONTROLLER

The ASEA robot's digital control computer has an unavoidable 0.280 second delay and cannot be used for high gain force feedback control. One possible approach to get force feedback control working is to bypass the digital controller entirely. This approach, referred to here as the "Analog Force Control (AFC)" approach, proposes an electronic hardware modification to the axis control of the robot. The approach takes advantage of digital position control/analog velocity control structure used by the ASEA controller. The digital position controller is physically disconnected and replaced by an analog velocity controller. Since this method uses analog electronics, the controller delay is completely eliminated.

Analog voltages from the force/torque transducer are conditioned in an analog electronic circuit, which would then inject a voltage into the summing junction of the velocity control feedback loop for each of the robot's motor through an external tachometer input line.

By directly commanding the velocity of each motor to be proportional to the force, a single degree-of-freedom damping control algorithm is implemented about each axis.

4.2 IMPLEMENTATION

By giving the motor a new velocity command, the digital position controller will determine that a positional error exists and therefore it will attempt to compensate for this. The combination of two controllers for one axis results in violent oscillations. The obvious solution is to simply remove the position control input from the motor. The AFC therefore operates the robot without any position control from the ASEA.

There are other practical problems which were overcome, including the elimination of the motor brakes. This was done by running a zero velocity move command program on the ASEA robot. Another problem included the strong noise on the analog control electronics of the ASEA, due primarily to the high frequency switching of the pulse-width modulated (PWM) power amplifiers used for driving the motors. This problem was not able to be addressed due to the short time allowed for testing.

4.3 POSITIONAL RESPONSE TESTS

The initial test procedure for the AFC approach followed that used last year in determining the characteristics of the adaptive control of the ASEA robot. Initially, a square wave voltage was applied to each axis and the steady-state velocity was measured. The voltage-velocity relationship for each axis is:

TABLE 1
VELOCITY VS. VOLTAGE FOR DIRECT MOTOR CONTROL

AXIS 1:	147 in./sec./volt
AXIS 2:	41 in./sec./volt
AXIS 3:	65 in./sec./volt

4.4 FORCE RESPONSE TESTS

The base rotation axis was initially used for force control testing. A simple attenuation circuit was built to attenuate output voltages from the JR3 force/torque sensor before being connected to the ASEA axis control board. An initial gain of 0.02 volts/volt was used. For base rotation, the relationship between the amplifier gain K_a and the force feedback gain is:

$$K_f = 6.0 * K_a$$

Initial lead around tests proved that the robot did respond in a damping control mode. In fact, the robot's motion was considerably smoother with this approach than with the similar Adaptive Control lead around demonstration.

Initial impact tests were performed where the robot was given a constant bias voltage simulating a specific force set point. The robot ran at a constant velocity until impacting a rigid table, where it would attempt to apply a constant force command. When this test was previously performed with the Adaptive Control feature of the ASEA, the robot would make contact, jump away from contact several inches, again approach at constant velocity, and repeat the cycle. The jump away from contact behavior, indicative of instability, was observed only for very high force control gains with the AFC approach.

Using the gain values observed from this test, a 1 D.O.F. stability test was performed using a pin attached to the robot with break-away bolts. An experimental determination of the marginal stability gain was performed experimentally. Marginal stability occurred with the electronic gain K_a set at 0.035 or equivalently a force feedback control gain of 0.21 in./sec./lb. Notice that this value falls within the previously defined design specifications.

4.5 1 D.O.F. FORCE TRACKING TESTS

Force tracking tests were performed by using a single axis of an external three axis simulator table, designed to simulate the motion of the SSV on the pad. Typical test results are shown in Figure 6. Notice that the force appears 90 degrees out of phase with the position, or equivalently in phase with the velocity, as expected with the damping control approach. In this example, the force control gain K_f was set at 0.12 in./sec./lb., which corresponds well with the maximum observed velocity/force ratio of 0.11 in./sec./lb. Tracking tests were performed with speeds of up to 10.5 in./sec. with maximum force levels not exceeding 70 Lbs., indicating experimentally that the AFC approach can jointly meet both the tracking and stability requirements for force feedback control.

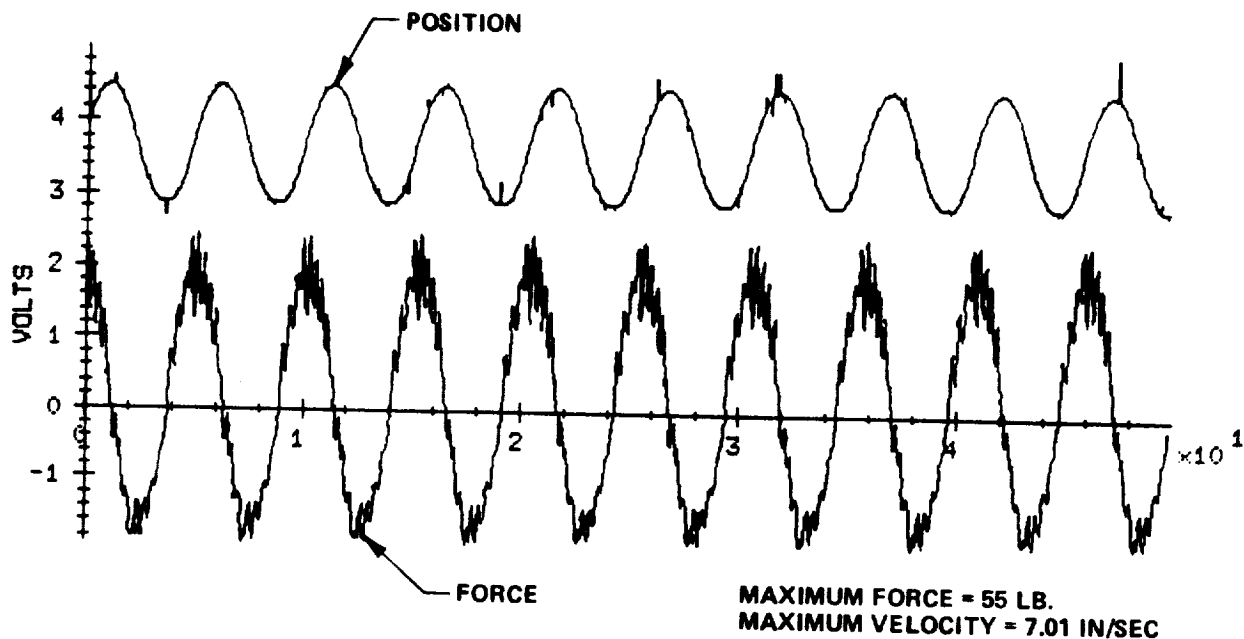


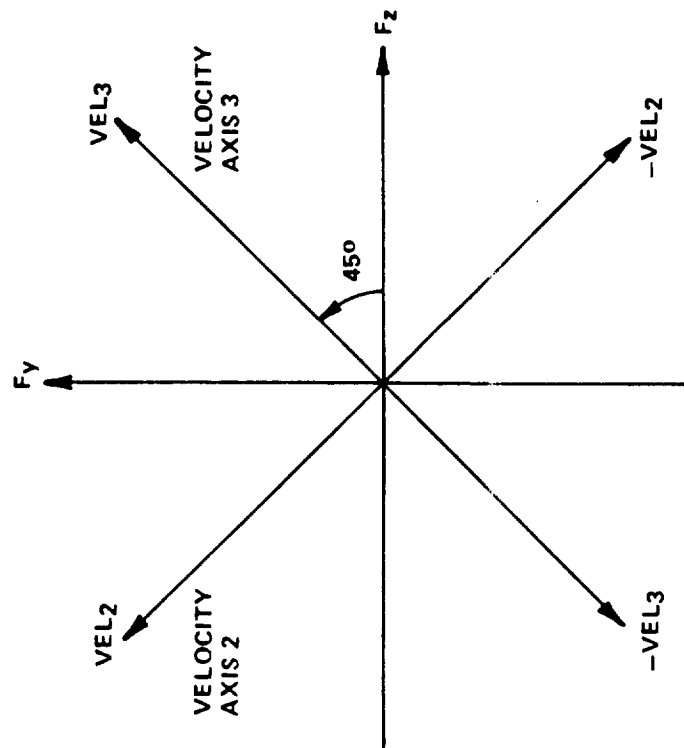
Figure 6. 1 D.O.F. Force Tracking Test
 $(K_f = 0.089 \text{ in/sec/lb})$

Problems occur when the range of travel along an axis is large enough so that the angle between the insertion pin and the receptacle becomes large. The angle where this becomes unacceptable is dependent on the flexibility of the pin as well as the chamfer of the receptacle. However, the robot was able to maintain contact over the maximum range of travel expected by the SSV. This orientation problem in one area where passive compliance will be vital to the umbilical mating project.

4.6 3 D.O.F. FORCE TRACKING TESTS

With the success of the 1 D.O.F. controller, the testing of a 3 D.O.F. analog force controller was the necessary next step. In the 1 D.O.F. case, the motion of the base rotation of the robot (axis 1) was in the X direction of the force/torque sensor, allowing the direct (SISO) control of the axis from the X direction force measurement. However such orthogonal relation between the robots axis does not occur for the remaining Y (vertical) and Z (inward) axes of the sensor. In effect, a MIMO solution must be found.

For a specific robot configuration compatible with its position for contact with the simulator table, the motion of the second and third joints is approximately 45 degrees off the Y and Z axes, as shown in Figure 7. The



$$\begin{bmatrix} \text{VEL2} \\ \text{VEL3} \end{bmatrix} = \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \end{bmatrix} \begin{bmatrix} V_2 \\ V_3 \end{bmatrix} \quad \text{ROBOT}$$

VELOCITY VOLTAGE

$$\begin{bmatrix} V_2 \\ V_3 \end{bmatrix} = K_s \cos 45^\circ \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} F_y \\ F_z \end{bmatrix} \quad \text{CONTROL}$$

V SENSOR GAIN

$$\begin{bmatrix} \text{VEL2} \\ \text{VEL3} \end{bmatrix} = K_s \cos 45^\circ \begin{bmatrix} K_1 & -K_1 \\ V_2 & K_2 \end{bmatrix} \begin{bmatrix} F_y \\ F_z \end{bmatrix}$$

$$\begin{aligned} \text{VEL2} &= K_1 K_s \cos 45^\circ (F_y - F_z) = K_1 \cos 45^\circ (V_y - V_z) \\ \text{VEL3} &= K_2 K_s \cos 45^\circ (F_y + F_z) = K_2 \cos 45^\circ (V_y + V_z) \end{aligned}$$

Figure 7. Force vs. Motor Axis Transform

simple transform shown can approximately relate desired rectangular motion with the necessary joint motion for small deviations about this point.

The electronic controller shown in Figure 8 was built to allow SISO control of Axis 1 as well as MIMO control of Axes 2 and 3. Offset adjustments were included for each motor, as was a set point bias on the Z axis to allow for a constant force set point in that direction.

Again the system was tested in the lead around mode. The decoupling of the Y and Z motion was not exact, but was within 5 degrees and was considered sufficient for tracking testing with the three axis simulator. For these tests, a rigid pin with break-away screws was used. The robot was initially guided into the receptacle, the force controller was started, and then table motion was begun. The robot was able to follow the table in all three axes, as shown in Figure 9 and on the videotape of the experiment. Due to a lack of time, only a cursory tuning of the second and third axis controller gains was performed. Therefore, tracking velocities for this test were lower than worst case conditions. Force levels remained fairly constant, reaching a maximum of 50 lbs. in the Y axis. This force is perhaps due to an axis bias problem.

4.7 SUMMARY

In summary, a simple 3 D.O.F. Analog Force Controller was built for 3 axis force feedback tracking of a moving target. The force control was sufficient in one axis to reach speeds of up to 10.5 in./sec. while keeping the forces below 70 lbs. The ability to track in 3 D.O.F. was demonstrated. Due to a lack of time, only a simple demonstration could be developed. However, all evidence indicates that with some refinement, this approach should be able to meet the design conditions for 3 D.O.F. force feedback control of the robot.

5.0 FUTURE DEVELOPMENT OF FORCE CONTROL FOR UMBILICAL MATING

5.1 EXTENSION TO 6 D.O.F.

The extension of this analog control approach to the orientation axes will require considerably more effort than the the simple analog force controller presented. The primary difficulty will be handling the coordinate transform between the force-torque sensor and the axes of the robot. This will require position information to be extracted from the ASEA. Further, the complexity of the MIMO interaction will be more difficult, resulting in

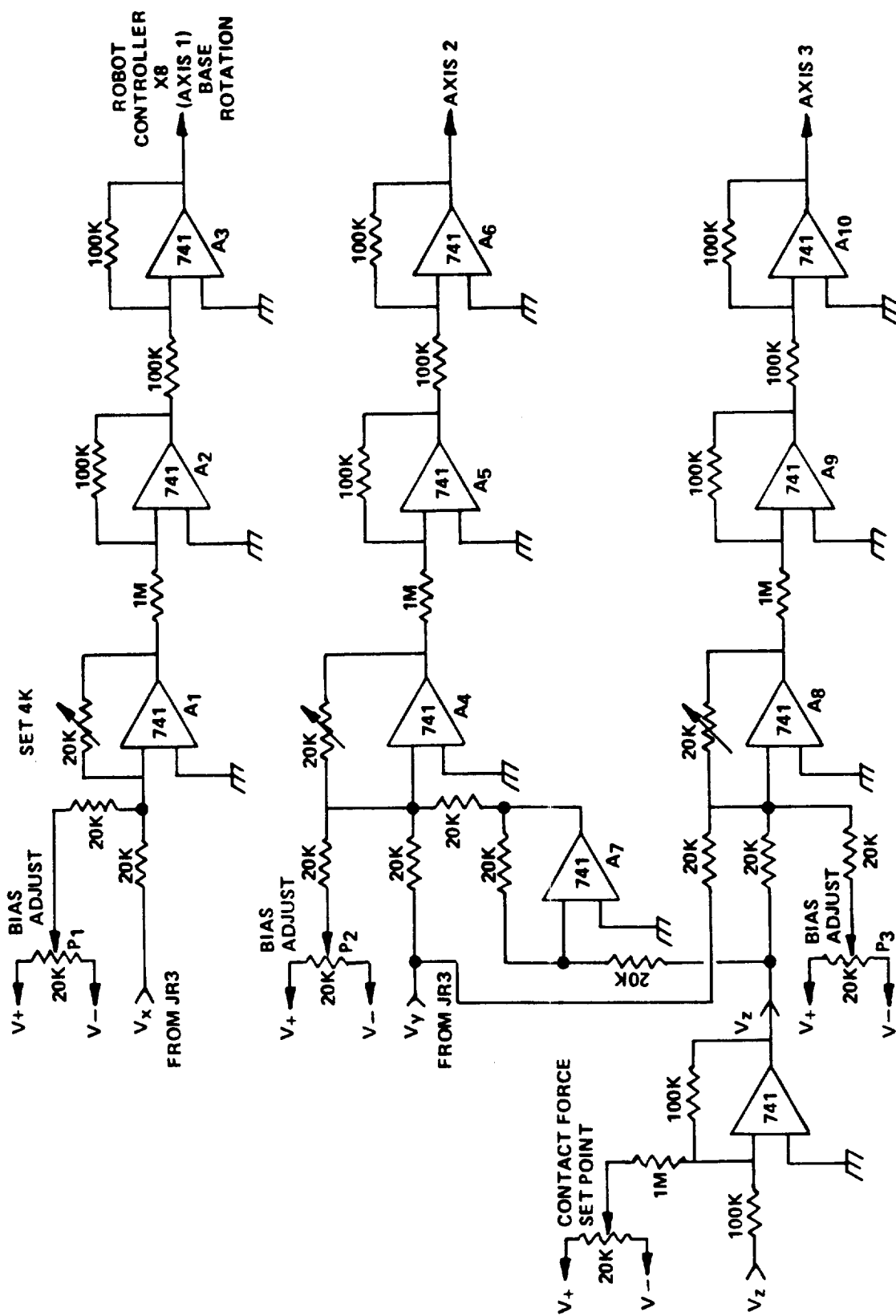


Figure 8. Analog 3 Axis Force Controller

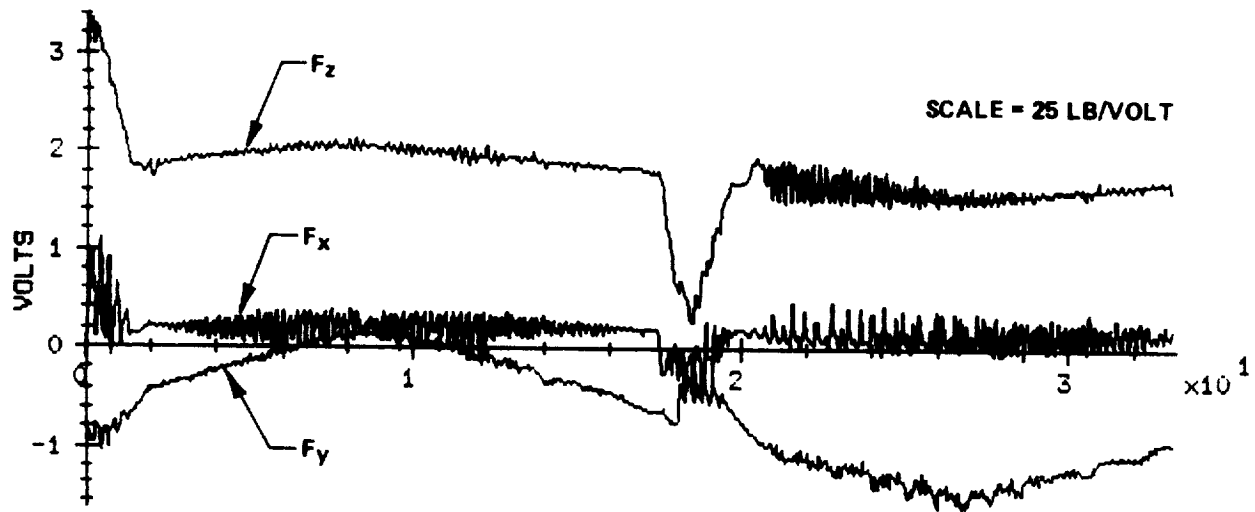


Figure 9. 3 D.O.F. Force Tracking Test

extensive interaction between the contact forces and the motion of the robot.

On an applied note, the three orientation axes use digital velocity control loops, rather than analog loops, as used by the three proximal axes. This requires direct control of the analog current loop. Also, disconnecting these axes from the robot triggers an ASEA controller fault, shutting down the robot. All of these problems will require considerable effort to achieve.

Note that there appears to be no immediate need for active orientation control for the initial umbilical mating test. Passive compliance should prove satisfactory for the short term.

5.2 FUTURE WORK ON FORCE FEEDBACK CONTROL

The following is a list of future tasks designed to improve the performance of the Analog Force Controller.

1. Professional construction of analog electronics controller card.
2. Electronically switchable robot interface.
3. Noise identification and suppression in electronics.
4. Circuit diagram of Op-Amp input to ASEA axis board.

5. Better joint coordination design.
6. Model for contact force.
7. Model-based controller tuning.
8. Integration with passive compliance.
9. 6 D.O.F. axis control investigation.

5.3 COMBINATION OF VISION AND FORCE

In the prototype umbilical mating tests, the force controller must work in conjunction with the existing 6 D.O.F. vision system. The integration of the two has been delayed until both force and vision have been capable of operating separately. The following is a possible senario of how vision can be combined with the 3 D.O.F. analog force controller.

POSSIBLE VISION/FORCE MATING PROTOCOL

1. 6 D.O.F. vision system brings robot to within force capture aperture.
2. MicroVAX II initiates control changeover from vision to force control by triggering electronic switchover to analog control of robot.
3. Strong force bias in Z direction from analog board moves robot into contact with target chamfers, force control in X and Y directions guides the robot to mated position. Passive compliance handles the orientation misalignments.
4. MicroVAX triggered collets rigidly attach flight-side and ground-side umbilical plates.
5. Bias in Z direction removed, force control allows robot to track motion of SSV.
6. MicroVAX triggers demate by first requests position information from ASEA controller to be used as a new baseline position for vision system.
7. MicroVAX switches control from analog to ASEA digital controller using vision system for withdrawl of robot.

5.4 SAFETY

There is a safety problem inherent any time two objects are in contact. This is especially true of the ASEA robot when used with the Analog Force Controller. To avoid injury, the analog controller should only be used by NASA and contractor personnel. One person should always be in direct contact with an emergency stop button. For protection of equipment, break-away pins should be used along with suitable current limits for both the robot and the simulator table.

5.5 CONCLUSIONS

The ASEA controller is not capable of providing high-speed sensory control. Efforts to use the force/torque sensors with the MicroVAX II for force feedback control will encounter instability problems similar to those encountered with the Adaptive Control functions of the robot. Force feedback will not work through either adaptive control port of ASEA or the MicroVAX II path without extensive control system development to provide compensation for the software lags in the ASEA controller.

An alternate solution is to switch the existing servo control system between the digital and an additional analog controller for force feedback control. This form of force feedback control has been demonstrated to provide satisfactory performance for three D.O.F force feedback control without using passive compliance devices.

The 3 axes of AFC system can be coupled with passive compliance for the orientation axes and the vision system for initial target approach to satisfy a preliminary remote umbilical demonstration. However, the 3 D.O.F. analog force controller is not a very satisfactory solution, and future developments requiring force feedback control will be severely limited.

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